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(54) **NANOSTRUCTURED ANODE FOR HIGH CAPACITY RECHARGEABLE BATTERIES**

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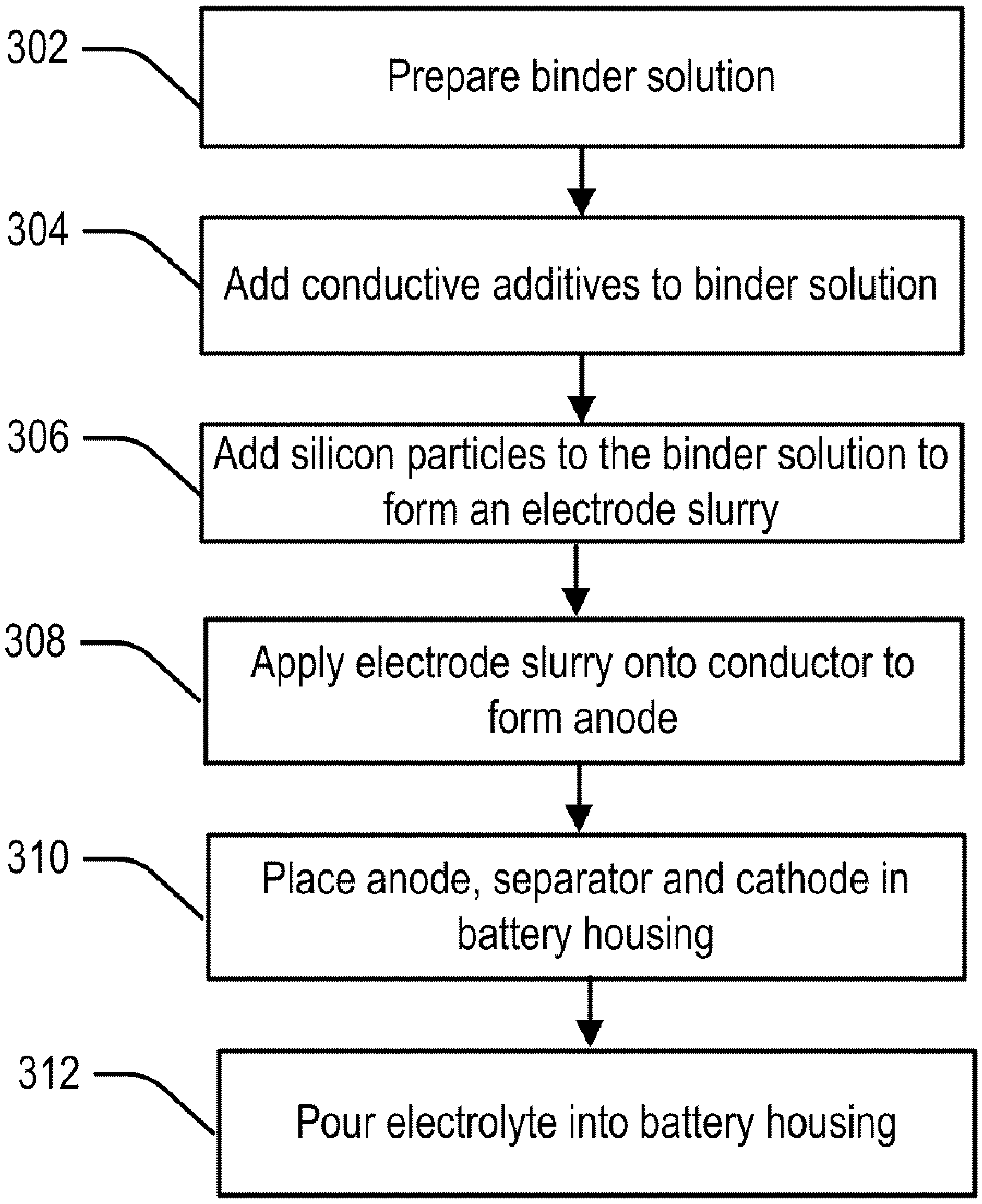
(57) **ABSTRACT**

Nanostructured anodes for high capacity rechargeable batteries are provided according to various aspects of the disclosure. The nanostructure anodes may comprise silicon nanoparticles for the active material of the anodes to increase the storage capacity of the batteries. The silicon nanoparticles are able to move relative to one another to accommodate volume expansion during lithium intercalation, and therefore mitigate active material degradation due to volume expansion. The anodes may also comprise elastomeric binders that bind the silicon nanoparticles together and prevent capacity loss due to separation and electrical isolation of the silicon nanoparticles.



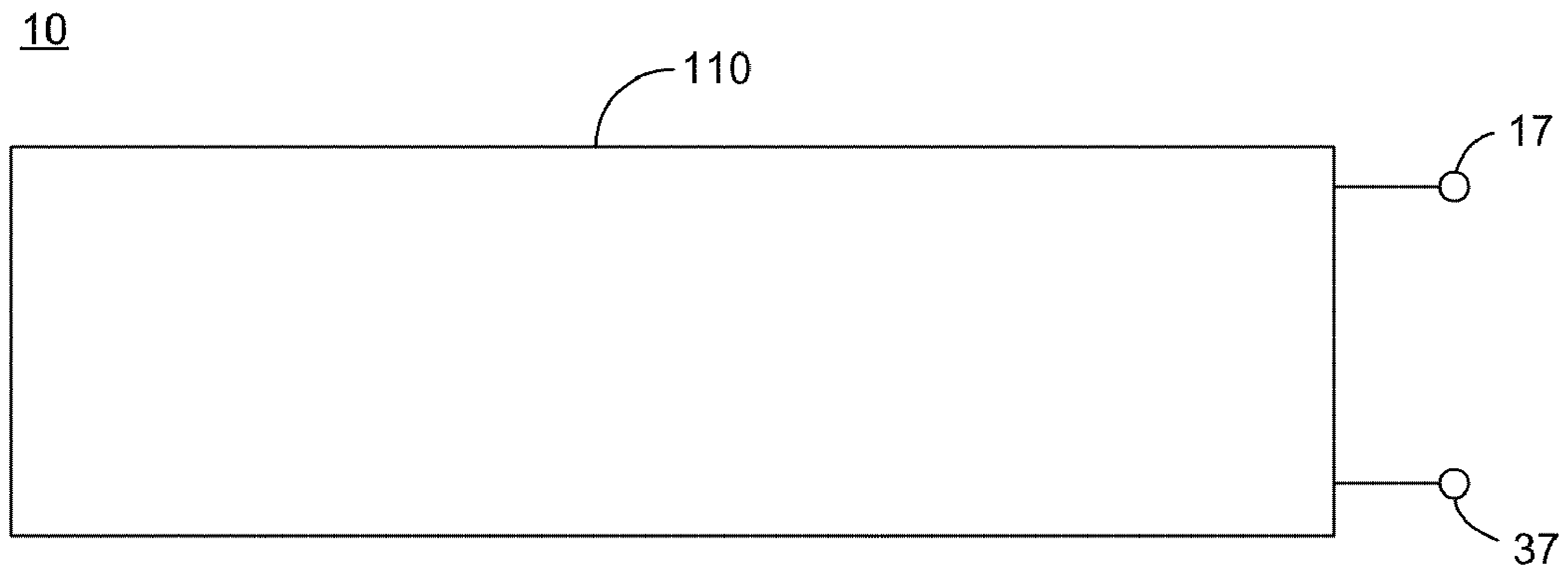


FIG. 1A

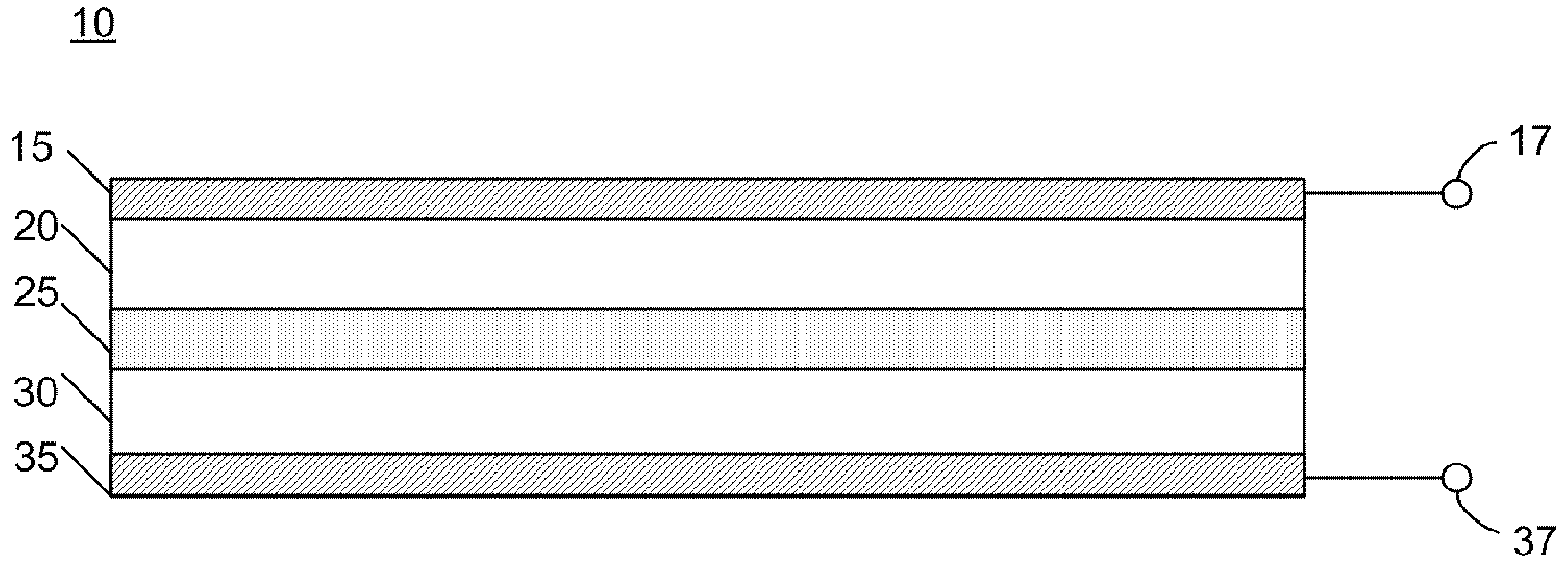


FIG. 1B

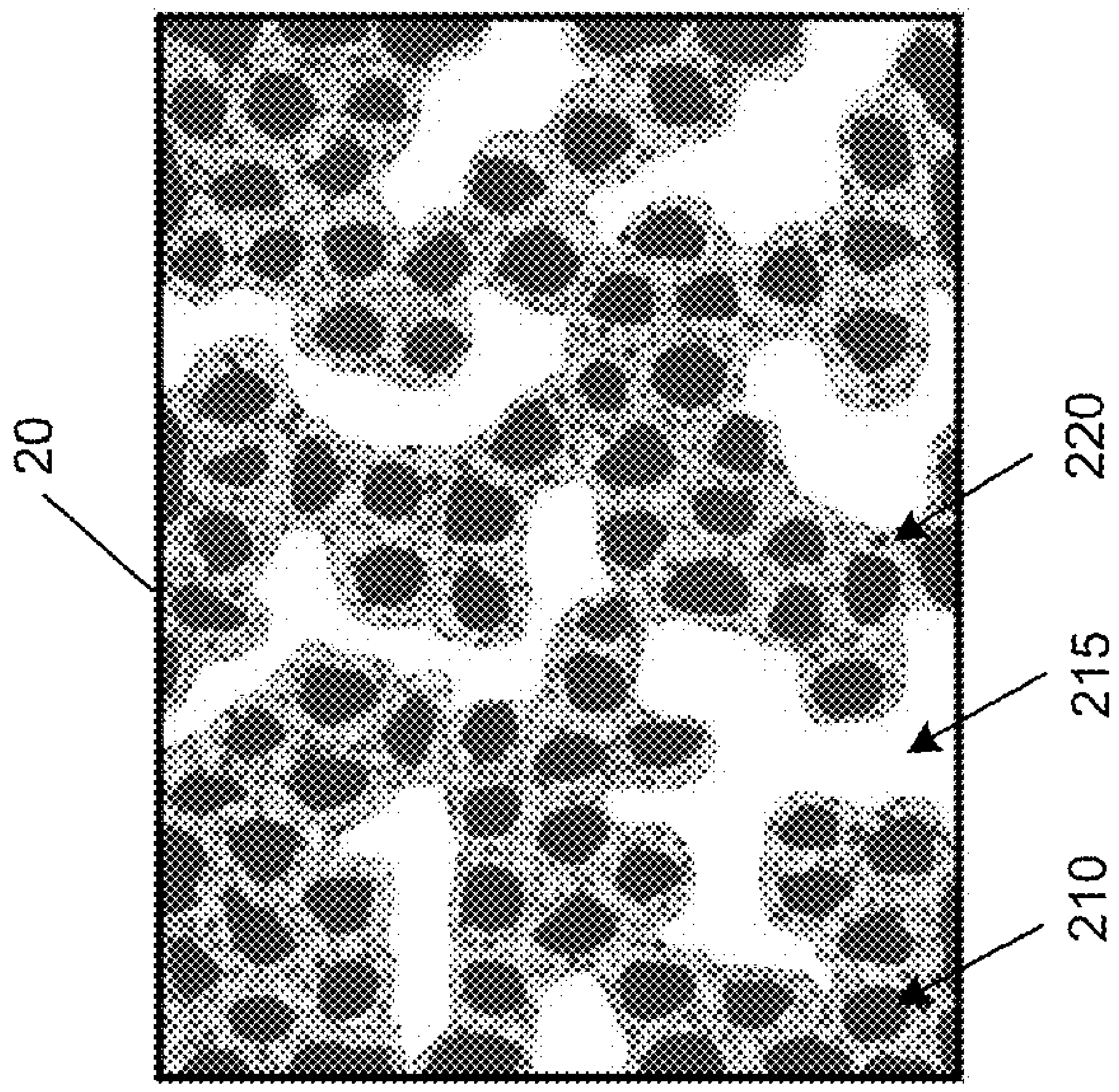


FIG. 2A

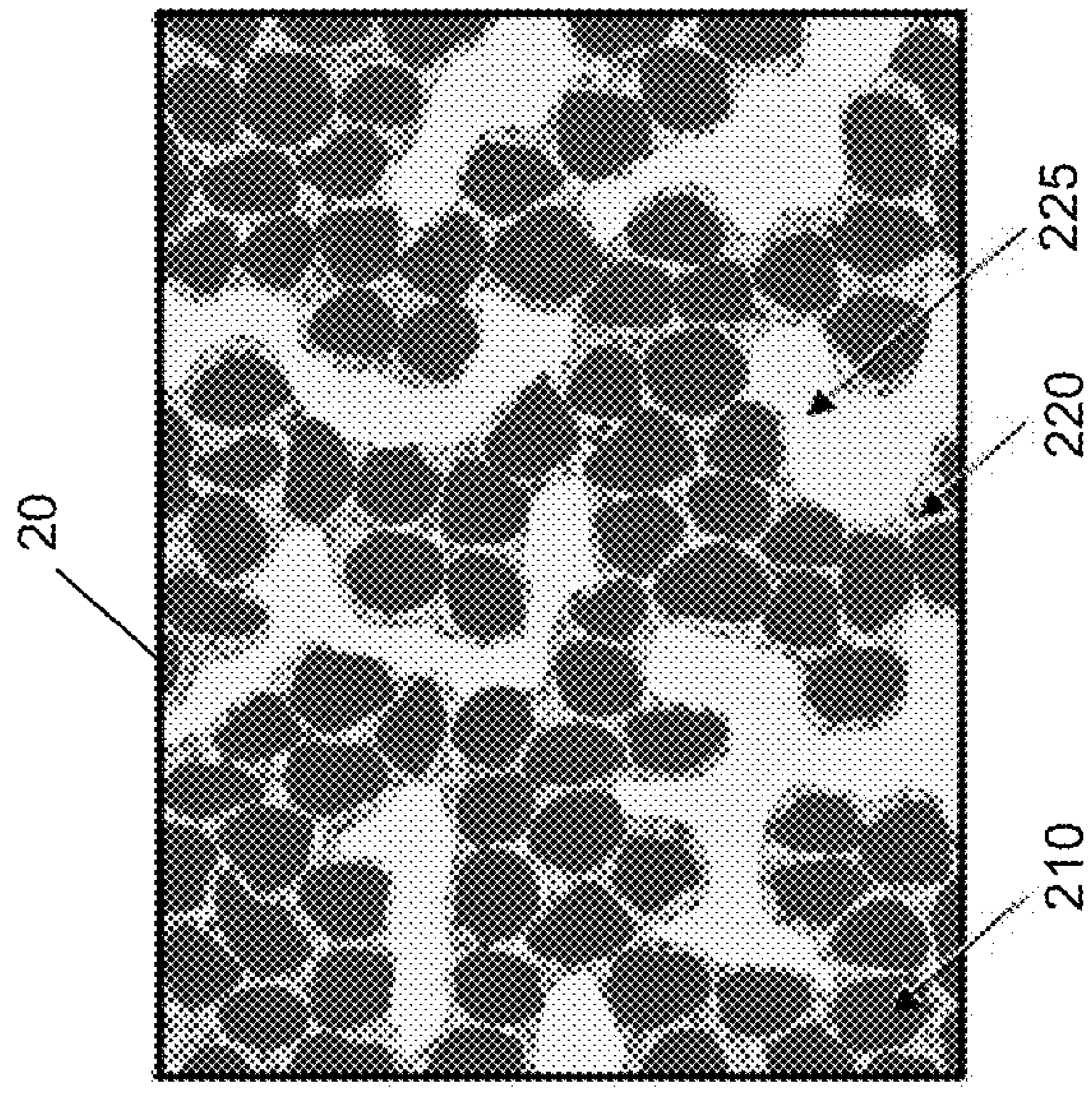


FIG. 2B

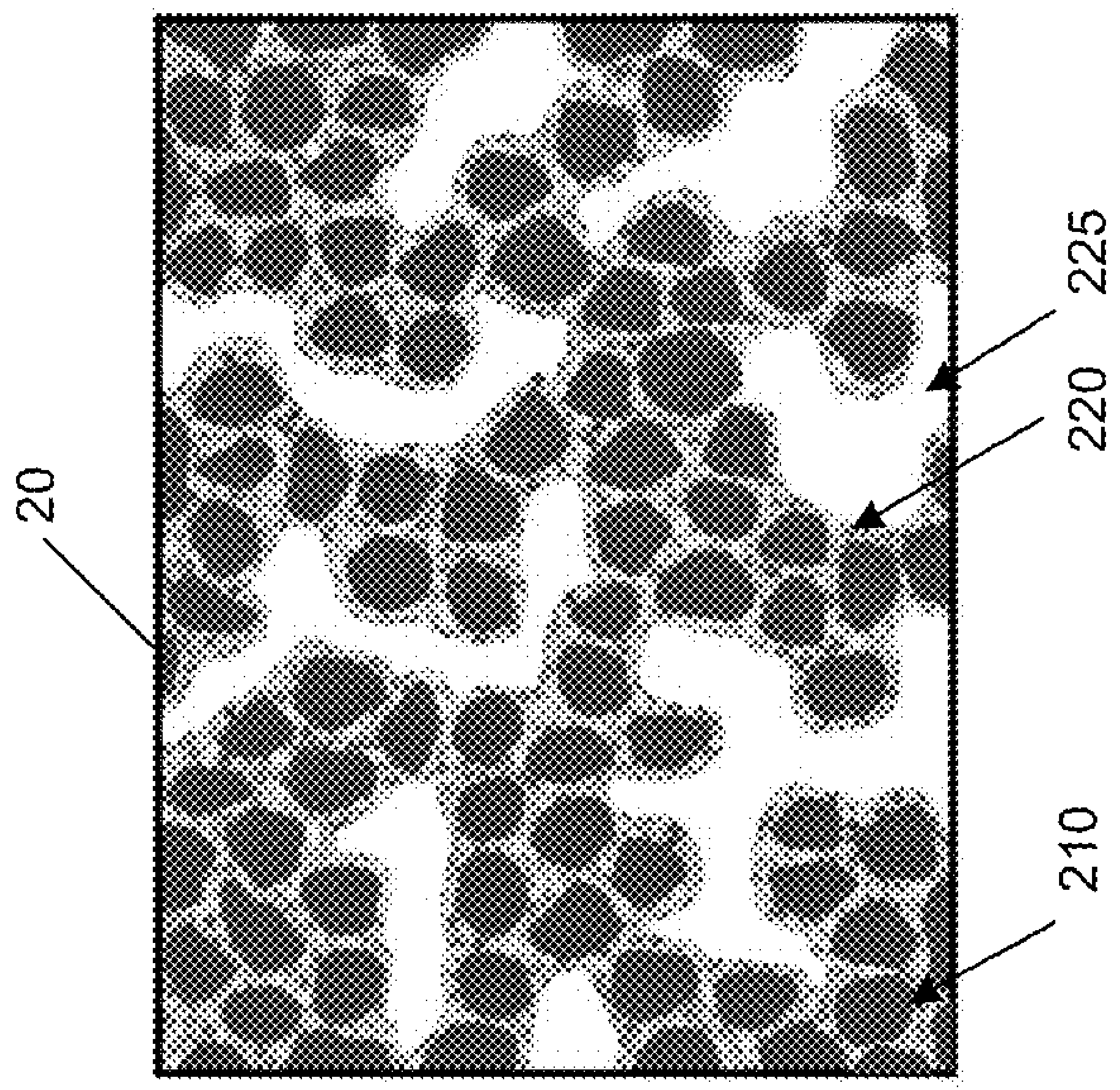


FIG. 2C

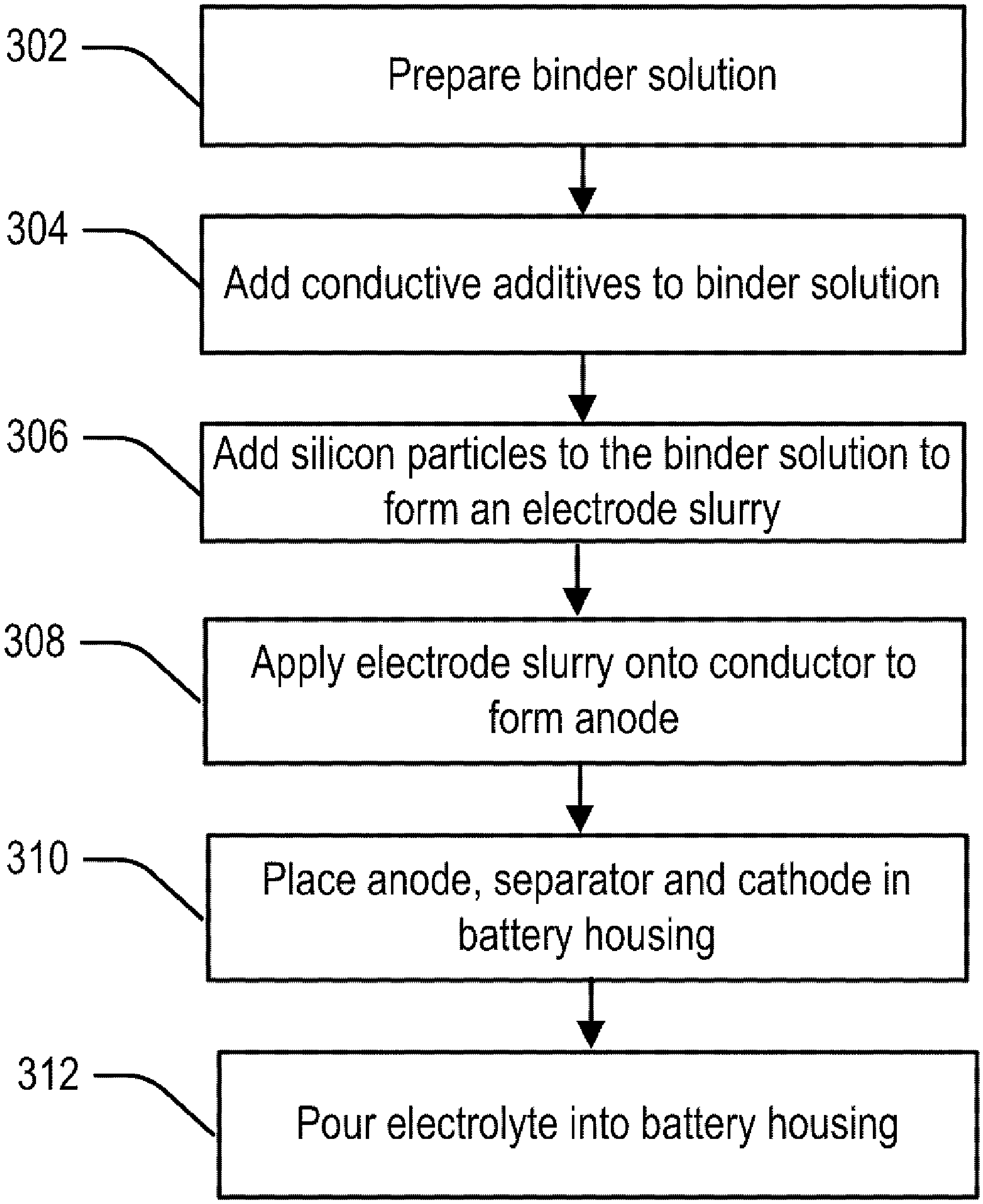

302
Prepare binder solution
304
Add conductive additives to binder solution
306
Add silicon particles to the binder solution to form an electrode slurry
308
Apply electrode slurry onto conductor to form anode
310
Place anode, separator and cathode in battery housing
312
Pour electrolyte into battery housing

FIG. 3

NANOSTRUCTURED ANODE FOR HIGH CAPACITY RECHARGEABLE BATTERIES

RELATED APPLICATION

[0001] The present application claims the benefit of priority under 35 U.S.C. §119 from U.S. Provisional Patent Application Ser. No. 61/096,262, entitled "NANOSTRUCTURED ANODE FOR HIGH CAPACITY RECHARGEABLE BATTERIES," filed on Sep. 11, 2008, which is hereby incorporated by reference in its entirety for all purposes.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not Applicable.

FIELD OF THE INVENTION

[0003] The present invention relates generally to batteries, and more particularly to nanostructured anodes for high capacity rechargeable batteries.

BACKGROUND OF THE INVENTION

[0004] There is growing demand for high performance rechargeable batteries in applications ranging from cell phones to satellites, including hybrid vehicles, portable electronics, and advanced space and military applications.

[0005] Lithium-ion batteries are commonly used for high performance rechargeable batteries. The storage capacity of conventional lithium-ion batteries is limited by the active material. In typical batteries graphite is used, which has a theoretical specific capacity of about 372 mAh/g. Silicon is an attractive material for lithium-ion anodes because of silicon's much higher theoretical specific capacity of about 4200 mAh/g. Thus, silicon-based anodes have the potential to dramatically improve the storage capacity of lithium-ion batteries. However, silicon-based anodes suffer from poor cycle life, which is attributed to active material degradation resulting from the large volume change that silicon undergoes during lithium intercalation.

SUMMARY OF THE INVENTION

[0006] Nanostructured anodes for high capacity rechargeable batteries are provided according to various aspects of the disclosure. The nanostructure anodes may comprise silicon nanoparticles for the active material of the anodes to increase the storage capacity of the batteries. The silicon nanoparticles are able to move relative to one another to accommodate volume expansion during lithium intercalation, and therefore mitigate active material degradation due to volume expansion. The anodes may also comprise elastomeric binders that bind the silicon nanoparticles together and prevent capacity loss due to separation and electrical isolation of the silicon nanoparticles.

[0007] In one aspect of the disclosure, a rechargeable battery is provided. The rechargeable battery comprises an anode, a cathode and an electrolyte for transporting lithium ions between the anode and the cathode. The anode comprises a plurality of silicon nanoparticles and an elastomeric binder binding the plurality of silicon nanoparticles together.

[0008] In another aspect of the disclosure, a method for fabricating an anode of a rechargeable battery is provided. The method comprises preparing a binder solution, adding conductive additives and silicon nanoparticles to the binder solution to form an electrode slurry, applying the electrode slurry onto a conductor, and drying the electrode slurry on the conductor to form the anode.

[0009] Additional features and advantages of the invention will be set forth in the description below, and in part will be apparent from the description, or may be learned by practice of the invention. The advantages of the invention will be realized and attained by the structure particularly pointed out in the written description and claims hereof as well as the appended drawings.

[0010] It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory and are intended to provide further explanation of the invention as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. **1**A shows an example of a battery according to an aspect of the disclosure.

[0012] FIG. **1**B shows the battery comprising an anode, a separator and a cathode according to an aspect of the disclosure.

[0013] FIG. **2**A shows an anode comprising silicon nanoparticles and an elastomeric binder according to an aspect of the disclosure.

[0014] FIG. **2**B shows the anode in a charged state after lithium intercalation according to an aspect of the disclosure.

[0015] FIG. **2**C shows the anode in a discharged state after lithium extraction according to an aspect of the disclosure.

[0016] FIG. **3** is a flow diagram illustrating a process for fabricating a battery according to an aspect of the disclosure.

DETAILED DESCRIPTION OF THE INVENTION

[0017] FIG. **1**A shows a high capacity rechargeable battery **10** according to an aspect of the disclosure. The rechargeable battery **10** comprises a battery housing **110** and first and second terminals **17** and **37**, respectively. During discharging, the battery **10** supplies power to an external circuit with the first terminal **17** acting as the negative terminal and the second terminal **37** acting as the positive terminal of the battery **10**. During charging, the battery **10** stores energy from a charger.

[0018] FIG. **1**B shows the rechargeable battery **10** without the battery housing **110**. The battery **10** comprises a first conductor **15**, an anode **20**, a separator **25**, a cathode **30** and a second conductor **35**. The first conductor **15** is electrically coupled to the first terminal **17** and the second conductor **35** is electrically coupled to the second terminal **37**. In one aspect, the first and second conductors **15** and **35** may extend beyond the anode **20** and the cathode **30** to form the first and second terminals **17** and **37**, respectively. The first conductor **15** may also be referred to as a current collector.

[0019] In one aspect, the battery housing **110** holds lithium ions in an electrolyte, which may comprise lithium salts dissolved in a solvent. The electrolyte is used to provide aqueous ionic transport of lithium ions between the anode **20** and the cathode **30** through the separator **25**. The separator **25** may be made of a porous material that electrically isolates the anode **20** from the cathode **20** while allowing lithium ions to pass through.

[0020] To charge the battery **10**, lithium ions are extracted from the cathode **30** and transported in the electrolyte to the anode **20**, where the lithium ions intercalate into the active material of the anode **20**. To supply power to an external circuit, the battery **10** is discharged from the charged state.

During discharging, lithium ions are extracted from the active material of the anode **20** and transported to the cathode **30** through the separator **25**. This process releases electrons in the active material of the anode **20**, which are collected by the first conductor **15**. The collected electrons flow to the external circuit through the first terminal **17**, which acts as the negative terminal of the battery **10** during discharging. The lithium ions transported to the cathode **30** intercalate into the active material of the cathode **30**. This process requires electrons, which are supplied to the active material of the cathode **30** from the second conductor **35**. The second conductor **35** may receive the electrons from the external circuit through the second terminal **37**, which acts as the positive terminal of the battery **10**.

[0021] In conventional lithium-ion batteries, the active material of the anode **20** comprises graphite, which has a practical specific capacity of about 350 mAh/g. Silicon has a much higher practical specific capacity of about 3580 mAh/g. As a result, an active material comprising silicon can hold much more lithium in the charged state than an active material comprising graphite, and can therefore dramatically increase the storage capacity of the battery **10**.

[0022] Because of silicon's high capacity to hold lithium, silicon undergoes a large volume expansion during lithium intercalation when used for the active material of the anode **20**. For example, amorphous silicon having a specific capacity of about 3580 mAh/g can increase in volume by 280% when lithium ions intercalate into the silicon to charge the battery **10**. This large volume expansion can lead to active material degradation, resulting in a loss of storage capacity of the battery **10** over charge/discharge cycles.

[0023] Active material degradation due to volume expansion can be mitigated by using silicon nanoparticles for the active material of the anode **20**. The silicon nanoparticles are able to move relative to one another to make room for lithium intercalation. However, separation of the silicon nanoparticles to accommodate the large volume expansion can create voids between the silicon nanoparticles when the battery **10** is subsequently discharged. These voids can cause silicon nanoparticles to become electrically isolated. As a result, electrons are unable to conduct between the electrically isolated silicon nanoparticles and the first conductor **15**, leading to a loss of capacity of the battery **10**.

[0024] In an aspect of the disclosure, an elastomeric binder is used to bind the silicon nanoparticles in the anode **20** together and prevent electrical isolation of the silicon nanoparticles. FIG. **2**A shows an example of the anode **20** according this aspect of the disclosure. The anode **20** may have a thickness in the range of 5 to 500 microns. The anode **20** comprises silicon nanoparticles **210**, which are used for the active material of the anode **20**. The silicon nanoparticles **210** may have diameters of less than one micron.

[0025] The anode **20** also comprises the elastomeric binder **220** binding the silicon nanoparticles **210** together. The binder **220** may be electrically conductive to conduct electrons between the silicon nanoparticles **210** and the first conductor **15**. In one aspect, the binder **220** is able to stretch and contract to accommodate large volume changes in the silicon nanoparticles **210** while maintaining electrical conduction between the silicon nanoparticles **210** and the first conductor **15** through the binder **220**. As a result, the binder **220** prevents electrical isolation of the silicon nanoparticles **210** due to large volume changes, thereby reducing capacity loss from cycling and improving the cycle life of the battery **10**.

[0026] The binder **220** may comprise carboxy methyl cellulose (CMC), styrene butadiene rubber (SBR), polyurethane, polyimides, polyamides or a combination thereof. The silicon nanoparticles **210** may be covalently bonded to the binder **220**. In one aspect, silicon nanoparticles **210** are chemically functionalized with binder components and/or functional groups that bind with the binder **220**. These components may include monomers of an elastomeric polymer, prepolymers, or molecules with functional groups such as alcohols, carboxylates, or alkenes. The monomers may be the same elastomeric polymer that are used for the binder material. Modification of the surface of the anode **20** may take place at the particle surface or the oxide surface of a native oxide layer. The functionalized silicon nanoparticles **210** can then be covalently attached to the binder material **220**. According to this aspect, covalent attachment improves the active material-binder interaction, which prevents separation of the active material (silicon nanoparticles) and the binder **220** and therefore reduces capacity loss due to separation and electrical isolation of the active material over charge/discharge cycles.

[0027] Conductive additives (e.g., conductive carbon additives) may be added to the binder **220** to make the binder **220** conductive. In one aspect, the conductive additives in the binder **220** may comprise a combination of carbon black and graphite carbon. The carbon black may comprise carbon nanoparticles having diameters of less than one micron to provide particle-to-particle electrical conduction. The graphite carbon may comprise carbon strands having lengths of a few microns (e.g., 6 to 10 microns). The graphite carbon may be used to provide long electron conduction paths in the binder **220**.

[0028] In one aspect, the anode **20** includes pores **215** that allow the electrolyte to flow into the anode **20** and transport lithium ions to and from the silicon nanoparticles **210**. The anode **20** may have a porosity of 25 to 75%. The large surface area-to-volume ratio of the silicon nanoparticles **210** provides the lithium ions in the electrolyte with access to a large surface area of the active material (silicon) of the anode **20**.

[0029] FIG. **2**B shows the anode **20** in the charged state according to an aspect of the disclosure. In this aspect, the pores of the anode **215** are filled with an electrolyte **225** for transporting lithium ions. Individual lithium ions in the electrolyte are not shown in FIG. **2**B for ease of illustration. The electrolyte **225** may be prepared by dissolving lithium salt into a solvent. During charging, lithium ions in the electrolyte **225** intercalate into the silicon nanoparticles **210**, causing the silicon nanoparticles **210** to expand. FIG. **2**B shows the anode **20** in the charged state, in which the silicon nanoparticles **210** have larger volumes compared with the silicon nanoparticles **210** shown in FIG. **2**A due to lithium intercalation.

[0030] In this aspect, the binder **220** binding the silicon nanoparticles **210** together stretches to accommodate the volume expansion of the silicon nanoparticles **210** due to lithium intercalation. The binder **220** provides electrical conduction between the silicon nanoparticles **210** and the first conductor **15**, allowing electrons released during discharging to conduct from the silicon nanoparticles **210** to the first conductor **15**.

[0031] FIG. **2**C shows the anode **20** in a discharged state after discharging from the charged state shown in FIG. **2**B according to an aspect of the disclosure. During discharging, lithium ions are extracted from the silicon nanoparticles **210** and transported by the electrolyte **225** from the anode **20** to the cathode **30**. This causes the silicon nanoparticles **210** in the anode **20** to contract as shown in FIG. **2**C.

[0032] In this aspect, the binder **220** contracts to accommodate the volume reduction of the silicon nanoparticles **210**. After discharge, the silicon nanoparticles **210** remain bonded to the binder **220**, which provides electrical conduction between the silicon nanoparticles **210** and the first conductor **15**. The elastomeric binder **220** is robust to large volume changes of the silicon nanoparticles over charge/discharge cycles. Thus, the elastomeric binder **220** prevents separation and electrical isolation of the silicon nanoparticles **210** after discharge, and therefore reduces capacity loss of the battery **10** from cycling.

[0033] An example of a process for fabricating the battery **10** according to an aspect of the disclosure will now be discussed with reference to FIG. **3**.

[0034] In step **302**, a binder solution is prepared. The binder solution may be prepared by adding water or solvent to carboxy methyl cellulose (CMC), styrene butadiene rubber (SBR), polyurethane, polyimides, polyamides, polymer or a combination thereof. For example, the binder material may comprise sodium carboxy methyl cellulose (NaCMC) having a molecular weight (MW) of 90,000 and a degree of substitution (DS) of 0.7.

[0035] In one example, the binder solution is prepared by adding 142.5 g of DI water to 7.5 g of NaCMC (MW 90,000, DS 0.70) and mixing the mixture overnight. In this example, a 5% NaCMC binder solution is formed. The binder solution may also comprise a composite of CMC and SBR. The composite may comprise 25%-100% CMC with the remainder comprising SBR.

[0036] In step **304**, conductive additives are added to the binder solution. The conductive additives may comprise carbon nanoparticles, graphite carbon or a combination thereof. In one example, 3.25 g of Super P (carbon black) is added to 130 g of the 5% NaCMC binder solution to form a 2:1 NaCMC:Super P slurry. The conductive binder solution may be mixed with a homogenizer and placed in a sonicator for uniform dispersion. The binder solution may be mixed with the homogenizer for 5 minutes and the sonicator for 15 minutes. The binder solution may then be mixed further with the homogenizer for 5 minutes and the sonicator for 15 minutes.

[0037] In step **306**, silicon nanoparticles are added to the binder solution with the conductive additives to form an electrode slurry. The silicon nanoparticles may have diameters of 100 nanometers or less. In one example, 20 g of silicon nanoparticles are added to of 60 g ethanol to wet the silicon nanoparticles. The silicon nanoparticles may have diameters of 100 nm or less, e.g., 50 nm. 40 g of an ethanol and water solution having an ethanol to water ratio of 1:1 by weight is added to the wetted silicon nanoparticles to further wet the silicon nanoparticles. 117.6 g of the 2:1 NaCMC:Super P slurry is then added to the wetted silicon nanoparticles to form the electrode slurry. The silicon nanoparticles may also be wetted with a CMC solution. The wetting process makes the silicon nanoparticles more compatible with the binder material by chemically functionalizing the silicon with binder components and/or functional groups that bind with the binder material. The binder components may come from a CMC solution used to wet the silicon nanoparticles or the functional groups may come from OH functional groups of an alcohol (e.g., ethanol) used to wet the silicon nanoparticles. The electrode slurry may be mixed for a few minutes, e.g., 5 to 10 minutes, with a homogenizer.

[0038] In step **308**, the electrode slurry is applied onto a conductor to form the anode **20**. The applied electrode slurry may be dried and calendered to a desired anode thickness. In one example, the electrode slurry is cast onto a sheet of copper (e.g., 18 microns thick). A doctor blade with a 6 mil (approximately 150 microns) side is pulled down the copper sheet with the electrode slurry to form an even electrode film on the copper sheet. The electrode film is then air dried until all dark spots disappear and placed in a vacuum oven overnight at 70 C to fully dry. After drying, the electrode film is calendered to a target film thickness of approximately 50 microns. The dried electrode film forms a porous anode **20** and the copper sheet forms a first conductor **15** of the battery **10**. Thus, steps **302** to **308** of the process in FIG. **3** may be used to form the anode **20** of the battery **10**.

[0039] The anode material may comprise 60% to 90% silicon with the remaining amount comprising the binder material and conductive additives. The ratio of binder material to conductive additives may be 2:1 by weight or other ratio, e.g., 0.5:1 to 4:1.

[0040] In step **310**, the anode **20**, a separator **25** and a cathode **30** are placed in a battery housing **110**. The battery housing **110** may comprise an aluminized pouch or other container. The anode **20** and the cathode **30** may be stacked on one another with the separator **25** interposed between the anode **20** and the cathode **30**. The stack may be clamped together to ensure that the anode **20** and the cathode **30** stay in close contact with the separator **25**. The separator **25** may comprise Celgard 2400 or other porous material that allows ions to pass through while providing electrical isolation between the anode **20** and the cathode **30**. The cathode **30** may comprise lithium iron phosphate ($LiFePO_4$) or other material known in the art. The cathode **30** may be a phosphate, cobalt or nickel based. The cathode **30** may be attached to a second conductor **35**.

[0041] In step **312**, an electrolyte **225** is poured into the battery housing **110**. The electrolyte **225** may comprise lithium salt dissolved in a solvent. In one example, the electrolyte **225** may comprise $LiPF_6$ dissolved in a 1:1:1 solution of ethylene carbonate (EC), diethyl carbonate (DEC) and dimethyl carbonate (DMC). After the electrolyte is poured into the battery housing **110**, the battery housing **110** may be vacuum sealed with the first and second terminals **17** and **37** electrically coupled to the first and second conductors **15** and **35**, respectively.

[0042] When the battery **10** is initially charged, the electrolyte **225** may form a solid electrolyte interface (SEI) that provides electrical isolation between the silicon nanoparticles **210** and the electrolyte **225** while allowing lithium ions to conduct between the silicon nanoparticles **210** and the electrolyte **225**.

[0043] It is understood that the specific order or hierarchy of steps in the processes disclosed is an illustration of exemplary approaches. Based upon design preferences, it is understood that the specific order or hierarchy of steps in the processes may be rearranged. Some of the steps may be performed simultaneously. The accompanying method claims present elements of the various steps in a sample order, and are not meant to be limited to the specific order or hierarchy presented.

[0044] The previous description is provided to enable any person skilled in the art to practice the various aspects described herein. Various modifications to these aspects will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other aspects. Thus, the claims are not intended to be limited to the aspects shown herein, but is to be accorded the full scope consistent with the language claims, wherein reference to an element in the singular is not intended to mean "one and only one" unless specifically so stated, but rather "one or more." Unless specifically stated otherwise, the term "some" refers to one or more. Pronouns in the masculine (e.g., his) include the feminine and neuter gender (e.g., her and its) and vice versa. Headings and subheadings, if any, are used for convenience only and do not limit the invention.

[0045] In one aspect, the term "element(s)" may refer to a component(s). In another aspect, the term "element(s)" may refer to a substance(s). In yet another aspect, the term "element(s)" may refer to a compound(s).

[0046] Terms such as "top," "bottom," "front," "rear" and the like as used in this disclosure should be understood as referring to an arbitrary frame of reference, rather than to the ordinary gravitational frame of reference. Thus, a top surface, a bottom surface, a front surface, and a rear surface may extend upwardly, downwardly, diagonally, or horizontally in a gravitational frame of reference.

[0047] A phrase such as an "aspect" does not imply that such aspect is essential to the subject technology or that such aspect applies to all configurations of the subject technology. A disclosure relating to an aspect may apply to all configurations, or one or more configurations. An aspect may provide one or more examples of the disclosure. A phrase such as an aspect may refer to one or more aspects and vice versa. A phrase such as an "aspect" does not imply that such aspect is essential to the subject technology or that such aspect applies to all configurations of the subject technology. A disclosure relating to an aspect may apply to all aspects, or one or more aspects. An aspect may provide one or more examples of the disclosure. A phrase such an aspect may refer to one or more aspects and vice versa. A phrase such as a "configuration" does not imply that such configuration is essential to the subject technology or that such configuration applies to all configurations of the subject technology. A disclosure relating to a configuration may apply to all configurations, or one or more configurations. A configuration may provide one or more examples of the disclosure. A phrase such a configuration may refer to one or more configurations and vice versa.

[0048] The word "exemplary" is used herein to mean "serving as an example or illustration." Any aspect or design described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other aspects or designs.

[0049] All structural and functional equivalents to the elements of the various aspects described throughout this disclosure that are known or later come to be known to those of ordinary skill in the art are expressly incorporated herein by reference and are intended to be encompassed by the claims. Moreover, nothing disclosed herein is intended to be dedicated to the public regardless of whether such disclosure is explicitly recited in the claims. No claim element is to be construed under the provisions of 35 U.S.C. §112, sixth paragraph, unless the element is expressly recited using the phrase "means for" or, in the case of a method claim, the element is recited using the phrase "step for." Furthermore, to the extent that the term "include," "have," or the like is used in the description or the claims, such term is intended to be inclusive in a manner similar to the term "comprise" as "comprise" is interpreted when employed as a transitional word in a claim.

What is claimed is:

1. A rechargeable battery, comprising:

a first conductor;

an anode attached to the first conductor, the anode comprising:

a plurality of silicon nanoparticles; and

an elastomeric binder binding the plurality of silicon nanoparticles together;

a second conductor;

a cathode attached to the second conductor; and

an electrolyte for transporting lithium ions between the anode and the cathode.

2. The rechargeable battery of claim **1**, wherein the plurality of silicon nanoparticles have diameters of 100 nanometers or less.

3. The rechargeable battery of claim **1**, wherein the elastomeric binder includes conductive additives to conduct electrons between the first conductor and the plurality of silicon nanoparticles through the binder.

4. The rechargeable battery of claim **3**, wherein the conductive additives comprise carbon nanoparticles.

5. The rechargeable battery of claim **3**, wherein the conductive additives comprise carbon black, graphite or a combination thereof.

6. The rechargeable battery of claim **1**, wherein the elastomeric binder is covalently bonded to the silicon nanoparticles.

7. The rechargeable battery of claim **6**, wherein the elastomeric binder is covalently bonded to the silicon nanoparticles by carboxyl or alkoxy groups.

8. The rechargeable battery of claim **1**, wherein the elastomeric binder comprises carboxy methyl cellulose (CMC), styrene butadiene rubber (SBR), polyurethane, polyimides or a combination thereof.

9. The rechargeable battery of claim **1**, wherein the anode comprises 60% to 90% by weight of the plurality of silicon nanoparticles.

10. The rechargeable battery of claim **1**, further comprising a separator disposed between the anode and the cathode and configured to pass lithium ions while providing electrical isolation between the anode and the cathode.

11. The rechargeable battery of claim **1**, wherein the electrolyte comprises a lithium salt in a solvent.

12. A method for fabricating an anode of a rechargeable battery, comprising:

preparing a binder solution;

adding conductive additives and silicon nanoparticles to the binder solution to form an electrode slurry;

applying the electrode slurry onto a conductor; and

drying the electrode slurry on the conductor to form the anode.

13. The method of claim **12**, wherein the silicon nanoparticles have diameters of 100 nanometers or less.

14. The method of claim **12**, wherein the conductive additives comprise carbon nanoparticles.

15. The method of claim **12**, wherein the conductive additives comprise carbon black, graphite or a combination thereof.

16. The method of claim **12**, wherein the binder solution comprises carboxy methyl cellulose (CMC), styrene butadiene rubber (SBR), polyurethane, polyimides or a combination thereof.

17. The method of claim **12**, further comprising wetting the silicon nanoparticles prior to adding the silicon nanoparticles to the binder solution.

18. The method of claim **17**, wherein the silicon nanoparticles are wetted with a wetting solution comprising elastomer components, functional groups or a combination therefore.

19. The method of claim **11**, wherein the anode comprises 60% to 90% by weight of the silicon nanoparticles.

20. An anode formed on a conductor for a rechargeable battery, comprising:

a plurality of silicon nanoparticles;

an elastomeric binder binding the plurality of silicon nanoparticles together, wherein the elastomeric binder is attached to the conductor; and

conductive additives in the elastomeric binder for conducting electrons between the conductor and the plurality of silicon nanoparticles.

21. The anode of claim **20**, wherein the plurality of silicon nanoparticles have diameters of 100 nanometers or less.

22. The anode of claim **20**, wherein the conductive additives comprise carbon nanoparticles.

23. The anode of claim **20**, wherein the elastomeric binder is covalently bonded to the silicon nanoparticles.

24. The anode of claim **23**, wherein the elastomeric binder is covalently bonded to the silicon nanoparticles by carboxyl or alkoxy groups.

25. The anode of claim **20**, wherein the elastomeric binder comprises carboxy methyl cellulose (CMC), styrene butadiene rubber (SBR), polyurethane, polyimides or a combination thereof.

26. The anode of claim **20**, wherein the anode comprises 60% to 90% by weight of the plurality of silicon nanoparticles.

27. The anode of claim **20**, wherein the anode has a thickness of 5 to 500 microns.

* * * * *